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LABORATORY SIMULATION OF FLUID DYNAMICAL PROCESS
RELATED TO WINTER ARCTIC LEADS

Final Report for the ONR Contract No.
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by

H.J.S. Fernando
Department of Mechanical & Aerospace Engineering
Arizona State University
Tempe, AZ 85287-6106

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1. Introduction:

During the contract period, the principal investigator and his graduate associate C.Y.Ching worked on two major tasks. The first was to wind up some of the work initiated under the previous ONR contract on double-diffusive convection (no. N 00014-87-K-0423) and the second was to initiate laboratory experiments on leads-induced convection. The work performed under these two categories are described below.

2. Research on Oceanic Convection

2.1 Double-diffusive layering

A comprehensive series of experiments were carried out to investigate the layered convection that occurs in linearly salt-stratified fluids subjected to destabilizing buoyancy fluxes, in particular heating from below. Unlike previous work, turbulence in the convecting layers was explicitly taken into account in modelling heat and salt transports through these layers. It was shown theoretically that the thicknesses of convecting layers can be parameterized using an expression of the form $h_c \sim (q/N^3)^{1/2}$, where q and N are the buoyancy flux and the buoyancy frequency of background stratification, respectively. Accordingly, expressions were derived for thicknesses of the first and the rest of the convecting layers. Experimental results were found to be in good agreement with the proposed predictions.

Another set of experiments were performed to examine the role of turbulence in the migration of density interfaces that are located between convecting layers of a thermohaline staircase structure. Turbulence manipulators were used to suppress convective turbulence near the interface, and it was shown that the thicknesses of the convecting layers can be controlled by manipulating turbulent intensities within them. Based on these results and experimental observations made using two-layer stratified fluids, it was concluded that the interfacial migrations in thermohaline systems are largely controlled by the turbulent entrainment.

The interfacial migrations are usually slow, but under certain conditions the interfaces can migrate rapidly and merge with each other. A Richardson number criterion based on local energetics was advanced to predict the merger of layers; when the Richardson number based on the interfacial-layer thickness, the interfacial buoyancy jump and the convective velocity falls below about 2.0, rapid migrations are initiated..

The layered structure could not be generated in the laboratory under certain circumstances that involve relatively low heat fluxes and high buoyancy frequencies. Dimensional analysis show that $q/k_h N^2$, Prandtl number (Pr) and the Lewis number (τ) are the governing parameters that determine the formation or non-formation of the layers; here k_h is the thermal diffusivity. A large number of experiments were carried out covering a range of $q/k_h N^2$ and Pr, and the results on the formation/non-formation of layering were realized on a regime diagram.

2.2 Thermal Convection in Rotating Flows

An experimental study aimed towards improving our understanding of the effects of rotation on convective turbulence was carried out using a laboratory tank. Two sets of experiments, namely convective turbulence in non-rotating and rotating fluids, were performed. The former preceded the latter and acted as a guide to understand the effects of rotation. The experiments were performed in a convection chamber, capable of providing a constant heat flux from below. The ranges of Rayleigh flux number Ra_f and Taylor number Ta investigated were $10^{12} < Ra_f < 10^{13}$ and $10^9 < Ta < 10^{11}$. The principal results of the non-rotating experiments are as follows:

(i) The vertical and horizontal velocities, and the lengthscale of turbulence, away from the boundaries, scale well with the convective velocity w_* and the height of the convecting layer H, respectively. These velocities are approximately constant in the height interval $0.2 < z/H < 0.8$. The data, in particular those for the horizontal component, compare well with previous results obtained in laboratory tanks and in the atmosphere.

(ii) The r.m.s. buoyancy fluctuations and the mean buoyancy in the core of the convecting layer scale with q_0/w_*, where q_0 is the buoyancy flux.

(iii) Frequency spectra collapse equally well when scaled with either $\overline{T'^2}\tau$ or $\overline{T'^2}(H^2/q_0)^{1/3}$, with frequency being scaled with τ or $(H^2/q_0)^{1/3}$, respectively. Note that τ is the time scale where thermals are injected into the convective zone from the conductive boundary layer near the heated surface and $(H^2/q_0)^{1/2}$ is the time scale of the energy-containing eddies of the mixed layer. The scales based on τ were first proposed by Foster (1971; *Geophysical Fluid Dynamics*, 2, 201-217) and have been used for scaling temperature fluctuation spectra by Boubnov and Ivanov (1988; *Izv. Ocean & Atm Phys.*, 24, 361-367), whereas the scales based on $(H^2/q_0)^{1/3}$ were introduced in the present study.

The principal results of the rotating experiments are:

(i) The r.m.s. velocities in the mixed layer are affected by the rotation at a height $z \approx 4.5 (q_0/\Omega^3)^{1/2}$, or a location where the integral lengthscale is $l_r \approx 1.1 (q_0/\Omega^3)^{1/2} \approx 1.5(\varepsilon/\Omega^3)^{1/2}$; because of the inhibition of the growth of the lengthscales by the rotation, l_r can also be considered as the lengthscale of the mixed-layer turbulence. The r.m.s. horizontal and vertical velocities within a rotationally affected, convective, mixed layer scale with $(q_0/\Omega)^{1/2}$, with $\left(\overline{u'^2}\right)^{1/2} \approx 1.6(q_0/\Omega)^{1/2}$ and $\left(\overline{w'^2}\right)_r^{1/2} / \left(\overline{u'^2}\right)_r^{1/2} \approx 1$. These results suggest that the Rossby number within the mixed layer is a constant $Ro \approx 0.75$, and that the effects of rotation are quickly felt in all directions even though only the horizontal components are directly affected by the rotation.

(ii) The growth rate of a convective mixed layer in a homogeneous fluid is substantially reduced by the rotation. Although the entrainment-rate data show a good collapse when scaled with the Kolmogorov velocity $(q_0\nu)^{1/2}$ or the r.m.s. velocity of turbulence, $(q_0\Omega)^{1/2}$, implicit evidence provided by the layer-growth data in non-rotating experiments indicates that the latter may be the correct scale; here ν is the molecular viscosity.

(iii) Mean buoyancy and r.m.s. buoyancy fluctuations in the core of the mixed layer scale with $(q_0\Omega)^{1/2}$. The mean buoyancy gradient within the convective layer is much larger than that of the non-rotating case. The small size of the integral lengthscale, which restricts the eddy overturning to scales smaller than the depth of the fluid column, was attributed to this observation.

(iv) The temperature spectra were found to scale satisfactorily with $\overline{T'^2}\Omega^{-1}$, when the frequency is scaled with Ω. Further tests are necessary to ascertain the applicability of this scaling to high-Reynolds-number turbulent convection.

2.3 Temperature and Salinity Structure in the Northwestern Weddell Sea; A laboratory Perspective

Temperature and salinity data obtained from the northwestern Weddell Sea during March 1986 Antarctic Marine Eco-Systems in the Ice Edge Zone Experiment (AMERIEZ) reveal numerous thermohaline staircases in the thermocline separating warm deep water from the overlying colder, lower salinity winter water. Staircases in the upper, steeper portion of the thermocline were characterized by layers having vertical extents of 1-5 m. Layer thicknesses in the deeper, weaker portion of the thermocline were far greater, sometimes exceeding 100 m. The former staircases are referred to as Type A, and the latter as Type B. Vertical gradients in temperature and salinity decreased abruptly across the boundary between Type A and Type B staircase regions. Mean density ratios R_p were 1.52 and 1.36 over the depth intervals containing Type A and Type B staircases, respectively. Type A staircases were present at all sites sampled, whereas Type B staircases were present over approximately the central 50% of the area sampled.

Laboratory-derived results show that the observed time and vertical space scales for the Type B staircases are consistent with the notion that they are maintained by double diffusive processes. These results, combined with temperature-salinity analyses, lead us to suggest that the Type B staircase regime may have originated as a vertically convective feature within which staircases have formed and evolved continually through double diffusion. Laboratory-derived flux laws are used to estimate upward buoyancy flux due to heat flux through the Type B staircase regime of order 2×10^{-9} m^2 s^{-3}, consistent with values derived previously using oceanographic, atmospheric and sea ice data and an order of magnitude greater than computed double diffusive heat fluxes through the Type A staircase regime. The broad area coverage of Type B staircases, coupled with previous observation of these features at scattered sites throughout much of the Weddell Sea, suggests that they are widespread there and may play a significant role in regional vertical heat transfer.

2.4 Modelling of Entrainment Across Double Diffusive Interfaces

A model was developed to predict the rate of entrainment and detrainment and the conditions for equilibrium for diffusive boundaries of a double-diffusive fluid layer. The system consists of a stably stratified layer overlying a mixed, turbulently convecting layer. The results show that the entrainment/detrainment laws are strongly dependent on the operating parameter range. At equilibrium, the density stability ratio at the edge of the convection zone depends only on the ratio of molecular diffusivities. The predictions are in satisfactory agreement with the available experimental data at large values of salinity and temperature gradients.

3. Research on leads-Induced Convection

A laboratory experiment dealing with the evolution of a two-dimensional thermal released at the upper surface of a two-layer stratified fluid was carried out with the hope of gaining insight into leads-induced buoyant convection. The initial descent of the thermal was observed to be similar to that of a vortex pair. Subsequent evolution of the flow was found to be dependent on the Richardson number Ri of the interface, defined by $\Delta b l_D/w_D^2$, where l_D and w_D are the length and velocity scales of the thermal just prior to the impingement and Δb is the buoyancy jump. At high Richardson numbers, Ri > 10, upon impingement the thermals split into two separate vortices without deforming the density interface significantly. After some time, a front with a sharp nose angle emerges from each vortex, which travels along the density interface mainly as a result of the gravitational collapse. On the other hand, at small Richardson numbers, Ri < 5, the thermals penetrate deep into the density interface and bounce back owing to the baroclinic force. During rebound, they lose the characteristics of a vortex pair and immediately collapse along the density interface to form an intrusive gravity current. The maximum penetration of the thermal into the lower layer was found to be given by $\delta/l_D \cong 2.0\ Ri^{-1}$. The normalized propagation velocity of the gravity current along the density interface showed a slight increase with increasing Ri, from $U_f/(Q/D)^{1/2} \cong 0.4$ to $U_f/(Q/D)^{1/2} \cong 0.5$, where D is the depth of the upper layer and Q is the buoyancy flux per unit width. The horizontal secondary flow in the upper layer was found to have a maximum normalized velocity $U_e/(Q/D)^{1/2} \sim 0.2 - 0.3$, with U_e for the case Ri > 10 being somewhat higher. The impact of the thermal on the density interface generates a field of interfacial waves. When Ri >10, a dominant energy bearing frequency ω^* could identified whereas when Ri < 5, the energy was found to be generally distributed over a band of frequencies. The dominant frequency ω^* was well predicted by a theory due to Phillips (1977), when the wave length of the waves is scaled with the size by the thermal before the impingement. A pair of solitary waves are generated owing to the reflection of the gravity currents at the side walls. They propagate toward the center, collide and pass through each other. The velocity of the solitary waves c was found to be given by $c^2 \sim D_1 \Delta b$, where D_1 is the depth of the lower layer.

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